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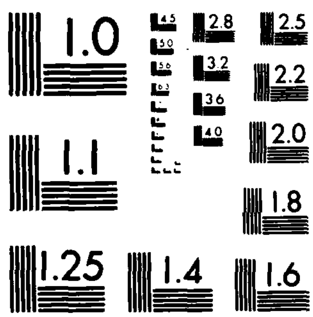

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TITLE: APPLICATION OF THE NEW PROPULSION THEORY TO THE DESIGN OF PROPELLERS. COMPARISON WITH THE LIFTING LINE THEORY

APLICACION DE LA NUEVA TEORIA DE LA IMPULSION AL DISENO DE PROPULSORES. COM-COMPARACION CON LA TEORIA DE LAS LINEAS SUSTENTADORAS

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APPLICATION OF THE NEW PROPULSION THEORY TO THE DESIGN OF PROPELLORS.

COMPARISON WITH THE LIFTING LINE THEORY

[G. Perez Gomez* **, I. Baquerizo Briones* and J. Gonzalez-Adalid Garcia--Zozaya*; Aplicacion de la Nueva Teoria de la Impulsion al Diseno de Propulsores. Comparacion con la Teoria de las Lineas Sustentadoras.; Ingenieria Naval, July 1983; pp. 267-278]

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Summary /267

Reference [15] criticized the traditional theory of axial propulsion by correcting and generalizing the basic hypotheses. After [12] the traditional mixed propulsion theory was criticized, and its errors were also corrected.

This work reveals the new propulsion theory and demonstrates its soundness by comparing it with the lifting line theory. In addition, examples are presented which show where this second theory is deficient and where, on the other hand, the new propulsion theory provides sound results and also reduces to 7% the amount of computer time needed to complete the design of a conventional propellor.

0 Introduction

Reference [15] presented the theoretical principles of a new theory of propulsion and demonstrated that the application which had traditionally been made of the theorum of momentum in order to relate the axial components of the velocities induced in infinity downstream from the propellor and in the disc of the propellor was incorrect.

The above-cited work demonstrated that correct application of the theorum of momentum does not produce a new equation, as traditionally assumed, but rather that an equation is obtained which is completely

*Numbers in the right margin indicate pagination in the original text.

identical to that which is arrived at by applying Bernouilli's theorum between infinity downstream from the propellor and infinity upstream from the propellor. This discovery removes all theoretical justification for the conclusion that both the tangential and the axial components of the velocities induced in the propellor disc must be half which [Translator's Note: this is an apparent misprint; may possibly be "of" because otherwise it leaves a clause without a predicate] the corresponding components in infinity downstream. /268

The above-mentioned work developed a new mixed propulsion theory which incorporated the conclusions given above into the traditional mixed theory.

When the above-mentioned ideas were applied in practice, it was thought that errors had traditionally been made in the development and use of mixed propulsion theory. These errors were pointed out and corrected in the 1982-1983 course edition of reference [12].

This work includes a summary of the final version of what the authors have agreed to call a new theory of propulsion and presents the results obtained in designing a propellor with the aid of a computer program developed by SATENA which is based on the above-mentioned theory.

The results obtained are compared with those which would be found with the classical lifting line theory, and it is deduced that when this theory is applied properly, the results coincide. Nevertheless, in those cases where the lifting line theory provides erroneous conclusions, the propulsion theory provides results which are completely consistent with reality.

The computer time required to carry out the hydrodynamic calculations corresponding to the design of a conventional propellor using the propulsion theory is on the order of 7% of that acquired by the lifting line theory. In the case of TVF [expansion unknown] propellors, the time required is only 2% of that necessary when using the lifting line technique.

It is therefore concluded that the theory which is presented here represents an important contribution to naval hydrodynamics which opens new horizons in the field of the design of marine propellors.

1. Explanation of the New Theory of Propulsion

1.1. Calculation of the Axial Components of the Induced Velocities

In accordance with the developments in Part 1 of [15], a model will be constructed of the effect exerted by the propellor on the fluid by means of a drive disc which is characterized by producing an underpressure between infinity upstream from the propellor and the propellor disc of magnitude $\theta\ \Delta p$ and an overpressure between the propellor disc and infinity downstream of the propellor of magnitude $(1 - \epsilon)\Delta p$.

The value of the coefficient ε must be between 0 and 1.

Assuming that an ideal fluid is involved and by applying Bernouilli's theorem to the fluid stream which traverses the propeller disc between the two regions of the fluid which are separated by the discontinuity surface which is represented by the propeller disc, the following equations are obtained:

Upstream from the propeller

$$p_\infty + \frac{1}{2}\rho v^2 = p - \varepsilon\Delta p + \frac{1}{2}\rho(v + \Delta v_1)^2 \tag{1}$$

Downstream from the propeller

$$p_\infty + \frac{1}{2}\rho(v + \Delta v_2)^2 = p + (1-\varepsilon)\Delta p + \frac{1}{2}\rho(v + \Delta v_1)^2 \tag{2}$$

Subtracting [as in text] equations (1) and (2), we obtain

$$\Delta p = \frac{1}{2}\rho[2v\Delta v_2 + (\Delta v_2)^2] = \rho\Delta v_2\left(v + \frac{\Delta v_2}{2}\right) \tag{3}$$

By multiplying the terms of the eouality given above by the area of the drive disc, the following is found:

$$T = A\Delta p = \rho A\left(v + \frac{\Delta v_2}{2}\right)\Delta v_2 \tag{4}$$

The above equality relates the thrust of the propeller to the density of the fluid, the area of the drive disc and the increment of velocity which the fluid experiences between less close to infinity upstream from the propeller and closer to infinity downstream.

By substituting the value of Δp which is obtained from equation (3) into either of equations (1) or (2), equation (5) is obtained which relates the axial components of the velocities induced in infinity downstream from the propeller and in the propeller disc

$$\Delta v_1 = -v + [(v + \varepsilon\Delta v_2)^2 + \varepsilon(1-\varepsilon)(\Delta v_2)^2]^{1/2} \tag{5}$$

1.2. Calculating the Induced Tangential Velocities

In order to be able to generalize the concept of a drive disc in such a way as to justify the existence of induced tangential velocities, it is necessary to assume that, in addition to producing an increment of pressure on the fluid, the disc is capable of producing a change in angular momentum in the water which traverses this disc.

Let I be the moment of inertia of the mass of water $\rho(v + \Delta v_1) A$ which traverses the drive disc per unit of time.

Suppose that the propeller returns at an angular velocity of ω.

In the arguments which are presented below, it will be assumed that the drive disc advances within the fluid at speed V, exerting on the fluid a thrust T and a turning moment M_1 and absorbing a turning moment M.

Below our attention will be focused on the same stream tube as was used in the previous section, i.e., allowance will be made for the fact that due to the effect of the continuity equation, the stream of liquid has a convergent aspect between infinity upstream from the propeller and infinity downstream [from it].

The moment M_1 which the drive disc exerts on the fluid must be completely invested by incrementing the moment of inertia of the fluid between infinity upstream from the propeller and infinity downstream from it, and it is thus possible to set

$$M_1 = I_\infty \Delta\omega \tag{6}$$

where $\Delta\omega$ is the increment of induced angular velocity in infinity downstream from the propeller and I_∞ is the moment of inertia of the water which flows through the stream of liquid in infinity downstream from the propeller.

When equation (6) was expounded allowance was made for the fact that the angular velocity of the fluid upstream from the propeller is zero.

If the propeller turns at an angular velocity ω and receives from the line of shafting a moment M, it will absorb an energy $M\omega$.

This energy will be invested in transmitting to the fluid a translational movement and a rotational movement.

The principle of the conservation of energy makes it possible to state

$$M\omega = T(v + \Delta v) + I_{\infty}\, \Delta\omega_1\, \Delta\omega \tag{7}$$

$\Delta\omega_1$ has been used to designate the angular velocity of the fluid as it passes through the drive disc.

We would like to emphasize that the above expression is completely different from that used by the classical authors. In the traditional development, the principle of the conservation of energy has been stated in the following terms:

$$M\omega = Tv + \frac{1}{2}\rho\,(v + \Delta v_1)\,(\Delta v_2)^2 + \frac{1}{2} I_{-\infty}\,(\Delta\omega_2)^2 \tag{8}$$ /269

The sum of the three summands of the second term of the above--indicated equality does not represent the total energy delivered by the drive disc to the fluid since in this balance no allowance was made for the pressure forces which operate when the fluid moves across the control surface.

On the other hand, the first summand of the second term of (7) represents the total energy which is invested in transmitting to the fluid the increment of velocity ΔV_2 in closer infinity and further infinity, while the second summand represents the total energy which is invested in producing the increment of angular velocity $\Delta\omega_2$ between the same limits. The sum of the two energies must coincide with the energy which the propeller receives from the rear shaft, and the two summands are exclusive and complementary with respect to M.

Then in the classical text (see, for example, [16]) the erroneous assumption that $M_1 = M$ is made, i.e., it is assumed that it is verified that

$$M = I_{-\infty}\, \Delta\omega_2 \tag{9}$$

This assumption is imprecise since a portion of moment M is invested in producing the thrust T.

In order to calculate the increment of velocity $\Delta\omega_1$ of the water as it passes through the propeller disc, it is sufficient to apply the theorem of the conservation of angular momentum from the drive disc to infinity downstream, stating that:

$$I_{-\infty}\, \Delta\omega_2 = I\, \Delta\omega_1 \;;\; \Delta\omega_1 = \Delta\omega_2 \frac{I_{-\infty}}{I} \tag{10}$$

If the theorem of angular momentum between infinity upstream and the propeller disc is applied, it is deduced that the induced angular velocity in the front face of the drive disc is zero.

The surface of discontinuity represented by the drive disc introduces an abrupt jump into the distribution of angular velocities in the fluid.

Note that this fact is ascertained clearly in the autopropulsion flow tests carried out on models. These tests quite clearly reveal that the jets located at the front of the propeller are oriented perpendicularly towards the propeller, and it is not possible to detect that they contain any tangential velocity components induced by the propeller on the fluid upstream from the propeller.

The preceding conclusion is not found, however, in the lifting line theory since if the Biot-Savart law is used to calculate the induced tangential velocity at any point in front of the propeller disc, finite components will be obtained.

1.3. Incorporation of Previous Developments Into the Design Calculations of a Propeller Which is Specially Adapted to a Wake Field

As we know, when a propeller which is adapted to a wake field is designed, regardless of what theory is used to calculate the velocities induced by the propeller, it is assumed that the overall behavior of the propeller can be predicted by integrating the behavior of all of the annular blade elements into which this propeller has been broken down in order to carry out the calculations.

In the preceding developments, an ideal propeller with uniform behavior throughout the entire disc was assumed. Nevertheless, it is reasonable to generalize these developments to the case where the stream tube breaks down into one of the stream tube shells which emerges as soon as the propeller disc is subdivided into annular elements.

Section 3 of [15] presented the appropriate refinements with respect to the process for generalizing the above material, and therefore we will not pursue this topic any further.

In the following it will be assumed that the radical* distribution of the thrust, per unit of length measured radically, which each annular element of the propeller must exert is known. This distribution may require a slight adjustment, which is always made by means of a relationship such that, in any case, the following is verified

$$T = \int_{r_h}^{R} dT \tag{11}$$

*sic, may be "radial"

Between the thrust dT of an annular element, the turning moment which this element receives from the propeller and the hydrodynamic pitch angle βi_o, there exist the following relationship

$$Z\ (dL \cos \beta i_o - dD \operatorname{sen} \beta i_o) = dT \tag{12}$$
$$Zr\ (dL \operatorname{sen} \beta i_o + dD \cos \beta i_o) = dM \tag{13}$$

Z is the number of blades in the propeller, and dL and dD are, respectively, the lifting and viscous resistance forces of the generic [may also be "common"] blade annular section. These forces will be given by

$$dL = \frac{1}{2} \rho v^{*2} C_r C_L dr \quad ; \quad dD = \frac{1}{2} \rho v^{*2} C_r C_D dr \tag{14}$$

where C_l and C_d are, respectively, the lift and viscous resistance coefficients of the generic blade annular section and C_r is the chord of this common annular section of the propeller which is under consideration.

The modulus of the velocity with which the water strikes the above-mentioned common annular section is

$$v^* = \{ [v_a (1 - w_n) + \Delta v_i]^2 + r^2 (\omega - \Delta \omega_i)^2 \}^{1/2} \tag{15}$$

Below is described the procedure which has to be followed to obtain the hydrodynamic pitch βi_o which corresponds to a generic annular section of the propeller.

These calculations will be carried out by assuming that the water behaves as if it were an ideal fluid and, therefore, in the statement presented below $C_D = 0$ will be assumed. Note that this hypothesis is also used in the lifting line theory.

From equalities (12) and (13), we find:

$$\frac{dM}{dT} = r \tan \beta i_o . \tag{16}$$

On the other hand, the following is verified:

$$\tan \beta i_o = \frac{v_a (1 - w_n) + \Delta v_i}{r (\omega - \Delta \omega_i)} \tag{17}$$

From this expression everything is known, with the exception of $\Delta\omega_1$. By substituting (16) and (17) into (7), the following is obtained:

$$dT\frac{v_a(1-w_a)+\Delta v_1}{\omega-\Delta\omega_1}\omega = \\ = T[v_a(1-w_a)+\Delta v_1]+I(\Delta\omega_1)^2 \tag{18}$$

By conducting operations, the following is arrived at:

$$\Delta\omega_1 = \frac{\omega - \left\{\omega^2 - \frac{4dT}{I}[v_a(1-w_a)+\Delta v_1]\right\}^{1/2}}{2} \tag{19}$$

By substituting the value of I into the preceding expression, the following is finally obtained:

$$\Delta\omega_1 = \frac{\omega - [\omega^2 - \frac{2dT}{\rho\pi r^3 dr}]^{1/2}}{2} \tag{20}$$

Of the two ~~route~~ signs [sic, no root signs given] the smaller was selected due to the fact that it provides better results. /270

Attention is called to the fact that the value of $\Delta\omega_1$ does not depend absolutely on ε, as we can see in expression (20). This means that there is decoupling between the axial and tangential components of the induced velocities.

From equation (20) it is deduced that the distribution of the tangential velocities depends on the speed of rotation of the propeller and the radial distribution of the propeller's load.

By substituting (20) into (17), the value of tan βi_o is obtained.

Once the radial distribution of the angle βi_o is known, it is possible to obtain the total values of M and T by integrating expressions (12) and (13). When these integrations were carried out, the appropriate values of the viscosity forces were introduced since otherwise the final values of T and M would have been incorrect.

In the case where, instead of imposing the thrust distribution law as an input datum, the principle of the distribution of the turning moment is employed, the procedure would be quite similar; it is just that the appropriate modifications would be made in the calculation process.

Finally, we would like to emphasize the extreme simplicity of the procedure for designing propellers which have been developed here in comparison with the classic [procedure involving] the Lerbs induction factors (lifting line theory) in which, in order to arrive at the final solution, it is necessary to repeatedly input matrices on the order of 17 x 17 throughout the calculation process, and conduct cumbersome expansions into Fourier series of the radial distributions of the induction factors. In addition, this procedure offers certain advantages in the theoretical area, which will also be commented upon below.

2. Application of the New Propulsion Theory To the Design of Propellers

2.1. Effect of the Parameter ε On the Magnitudes of the Axial Components of the Induced Velocities

The main problem which was encountered when an attempt was made to implement the ideas which were presented arose in finding the most suitable ε value for a given propeller since it is impossible to determine the value of Δv_1 unless a value is first established for ε.

Initially an attempt was made to derive the value of ε by calculating the areas of pressure distributions on the active and intake faces corresponding to various center lines which are commonly used in designing propellers.

The above-mentioned pressure distributions were calculated with the aid of the Theodorsen procedure, and it was noted that the quotient between the area corresponding to the intake face and the algebraic sum of the areas corresponding to the intake and pressure faces of the above-mentioned pressure distributions was approximately equal to 0.58 for any type of center line with which it [antecedent uncertain, probably "propeller"] operated at its ideal angle of attack. The value of ε which therefore would have to be introduced into the propeller design calculations, the complete behavior of which was known to SATENA was 0.58.

Once the first designs had been carried out, it was found that this value of ε provided some induced velocity values which were higher than those obtained with the lifting line theory.

Taking into account the fact that the propellers which were used in the comparisons had some outputs and a revolution adjustment which were very close to those calculated with the aid of the lifting line theory under both model and full-scale conditions, it was decided to adopt as correct the induced velocity values obtained with this theory.

After attempting to reproduce the design of the propellers which were mentioned above, it was concluded that the value of the coefficient ε which corresponded to conventional propellers should be between 0.40 and 0.43.

The difference between the actual value of ε and the estimated value is due to the fact that the theoretical calculations were carried out without allowance for the geometric pitch angle of the annular sections and the cascade effect caused by the annular sections of the other blades.

Later it was thought that if an attempt were to be made to reproduce, by the propulsion theory, the results obtained with the aid of the lifting line theory when it [presumably "the propulsion theory"] was found to be reliable, the best way to achieve this approximation would have to be to impose on the propulsion theory any one of the typical conclusions from the lifting line theory. Specifically, the condition that the induced axial velocities in the propeller disc were half of [Translator's Note: here again the word "which" is used] those induced in infinity downstream was imposed.

The value of ε with which it is noted that the value of the axial component of the velocity induced in the propeller disc is half of the corresponding value in infinity downstream is that derived from the following equalities:

$$\varepsilon = \frac{1}{2} \frac{v_a (1 - w_{ir}) + \frac{\Delta v_z}{4}}{v_a (1 - w_{ir}) + \frac{\Delta v_z}{2}} \tag{21}$$

It must be considered that if in the new propulsion theory a value of ε is used with which it is found that the induced axial velocities in the propeller disc are half of that in infinity downstream, this does not mean that the same is true of the tangential components since, as has been authoritatively demonstrated, the induced tangential velocity in the propeller disc does not depend absolutely on the coefficient ε.

In the following section it will be noted that, when working with values of ε which are derived from expression (21), with the new theory of axial propulsion we will arrive at values of tan Bi_o [sic, should be "βi_o"] which are very close to those obtained with the lifting line theory. However, the induced axial and tangential velocities are different in the two theories. The moduli of the vector V* (absolute velocity of the fluid with respect to the propeller disc) are indeed reasonably equal.

Below we will present an example which is very illustrative of the differences which exist between the lifting line theory and the new propulsion theory.

Consider an ideal propeller, the core of which is sufficiently large that it is possible to produce a certain circulation at the connection of the blades to the core [this term is uncertain, possibly "center"]. On the other hand, imagine that surrounding the blades of the propeller there is a nozzle which turns solidly connected to the propeller and that the blades of the propeller are designed in such a way that the value of the circulation along the entire blade is maintained constant.

Due to the fact that the lifting line theory considers that the induced velocities are the result of the radial variations in the circulation along the propeller blade, it can be stated that, from the standpoint of this theory, the tangential and axial components of the induced velocities of all of the annular sections of the propeller in its disc are zero.

In order to ensure that, from the standpoint of the new propulsion theory, it happens that the axial components of the velocities induced in the propeller disc are zero, the value of ε would have to be zero. This conclusion is not inconsistent with the theoretical formulation of the new propulsion theory and shows us that the increase in velocity which the fluid experiences when passing through the propeller disc takes place from the propeller disc towards infinity downstream; thus, this would be a propeller which would not suck upstream in absolute terms, such that in its drive disc model it would be characterized by significantly increasing the pressure from the disc towards infinity downstream, where the pressure is reestablished. /271

As we saw before, from the standpoint of the propulsion theory it is not feasible to imagine or assume that the induced tangential velocity can be zero. This fact marks the great difference which exists between the lifting line theory and the propulsion theory; the former would provide a propeller with a low pitch, while the latter would provide a design with some correct values of the angle Bi_o [possibly "βi_o"].

The preceding example was used to establish the connection which exists between the coefficient ε of the propulsion theory and the radial gradient of circulation which is used in the *lifting line theory.*

3. Comparison of the Results Obtained With the Lifting Line Theory With Those Obtained From the New Propulsion Theory

As promised in the summary of [15], below an interesting comparison will be made between the results obtained with the lifting line theory and with the new propulsion theory.

3.1. Brief Summary of the Characteristics of the LTDH26 Which was Developed at AESA [expansion unknown] and is Based On the Lifting Line Theory

The theoretical principles of this computer program were described in [10]. Later, [11] presented certain considerations which were of great interest in connection with the problems which had to be overcome in order to implement the ideas described in [10]. Finally, in the 1982--1983 course edition of [12] these considerations were included because it was considered that they were very formative.

On the occasion of the first Gaditana Naval Week, Mr. Ignacio Baquerizo, who took a very active part in the development of the LDTH26 program, discussed these topics in detail on June 30 and presented a great deal of information on the above-mentioned problem.

In this explanation the authors will limit themselves to noting the most relevant characteristics of this computer program so that these characteristics can be used to make a proper comparison between the potential of the lifting line theory and that of the new propulsion theory which was just presented in the preceding section.

As we know, the magnitudes of the velocities induced by a propeller are linearly dependent on the radial gradient of the law governing the distribution of circulation over the propeller blade.

The primitive developments of Lerbs were characterized by an attempt to calculate the velocities induced by the propeller on the basis of the proposed initial circulation distribution law. Nevertheless, the fact is that a circulation distribution law which is completely arbitrary is not necessarily consistent with the adjustment conditions desired for the propeller, and therefore in general it is necessary to introduce into the basic distribution law certain related transformations until the above-mentioned adjustment conditions are achieved.

In general, any type of circulation distribution law which a researcher attempts to impose will not necessarily prove to be useful since in the calculation process there may appear negative induced velocities which cause this type of law to be rejected because it constitutes a mathematical solution, but not a physical solution to the actual problem.

In order to avoid this problem, when the LDTH26 program was developed, it was decided that the input datum into this program would be the radial distribution law of the parameter $\tan \beta i_o / \tan \beta i$, instead of making it the circulation distribution law.

If the radial variation laws of this parameter which are characterized by the fact that their values remain equal to or greater than unity are defined, there is a high probability that the induced velocities will be positive when $\beta i_o > \beta i$.

It is obvious that, despite the imposed condition, negative induced velocities can also occur since, for this to happen, it would be sufficient for the induced tangential velocity to be positive and large and for the induced axial velocity to be negative and small. Nevertheless, the probability that such negative velocities will occur is considerably reduced and, moreover, if they should occur, it would be easy to eliminate them by sufficiently increasing the value of $\tan \beta i_o / \tan \beta i$ in the vicinity of the station [may also be "period of time", "condition"] where these negative induced velocities appear. Of course, this modification will be made without introducing discontinuities into the distribution of the above-cited parameter.

In order to find a transform of the initial distribution of the parameter $\tan \beta i_o / \tan \beta i$ which makes it possible for the propeller adjustment conditions to be verified, this parameter is expressed in the form: $1 + f(r)$.

In the process of iteration, the radial distribution of f(r) is progressively modified by means of related transformations of this distribution by multiplying this function by the quotient of the desired turning moment and the turning moment which is obtained if this is the base variable which is selected to implement the convergence or, on the other hand, by the quotient of the desired thrust and the thrust actually obtained if it is thrust which is selected as the variable for implementing the convergence.

One of the most important characteristics of the LDTH26 program is that the following parameters appear in it as input data:

a) Number of stations [see note above] which have to be utilized to define the radial distribution of the induction factors.

When the first checks were carried out with this computer program, it was verified that the precision of the calculations depended in principle on the quality with which the radial distribution law of the induction factors was defined. After the appropriate systematic variations were carried out, it was concluded that it was necessary to define any radial distribution law of the induction factors at at least 100 radial stations.

b) Number of harmonics of the expansion into a Fourier series of the radial distribution law of the induction factors which have to be incorporated into the calculations.

Following a procedure similar to that mentioned above, it was concluded that in order to obtain a sufficient degree of precision in the calculation of the induced velocities, it was necessary to use as few as the first 25 terms of the expansion into a Fourier series of the radial distribution laws of the induction factors.

c) The number of the stations which must be included in the integration of the radial distributions of turning moment and thrust. /272

After the appropriate checks were performed, it was concluded that the integration had to be carried out by defining the above-mentioned variables at at least 20 radial stations.

Figures 1, 2 and 3 give a simple definition of the flow chart of the above-mentioned computer program.

Finally, we should also mention that, when the calculations which are presented below were carried out, the standard values of the parameters mentioned above were used.

3.2. Description of the LDTH28 Computer Program Which Was Developed At SATENA and Is Based On the New Propulsion Theory

Figures 4, 5 and 6 show summary flow charts of the computer program written by Juan Gonzalez-Adalid, who, on the occasion of the most recent First Gaditana Naval Week on 30 June, presented a much more comprehensive description of the program.

At the same time as the above-mentioned computer program was written, a subroutine was developed at SATENA which was written by Mr. Jose Luis Lopez Lopez which quickly generates the data which have to be used in the calculation.

This generation extends to the radial distribution law of wakes, thrusts, thicknesses, chords, skewbacks, etc.

The above-mentioned subroutine utilizes the same mathematical function to generate the above-mentioned radial distribution, and only a total of 5 boundary conditions appear as input parameters.

This subroutine will be briefly extended to the LDTH26 program. /273

By way of examples, Figures 7, 8 and 9 show, respectively, the radial distribution laws of thrust per unit of length, the chords and the superpositions of the skewback and the radial distribution law of the chords. It must be mentioned that this law is generated automatically by imposing the disc-area relationship desired for the propeller as a boundary condition.

The integration of the radial distribution of the turning moments and thrusts was made using 50 radial stations. By the same token, the number of blade elements into which the propeller was subdivided was 50.

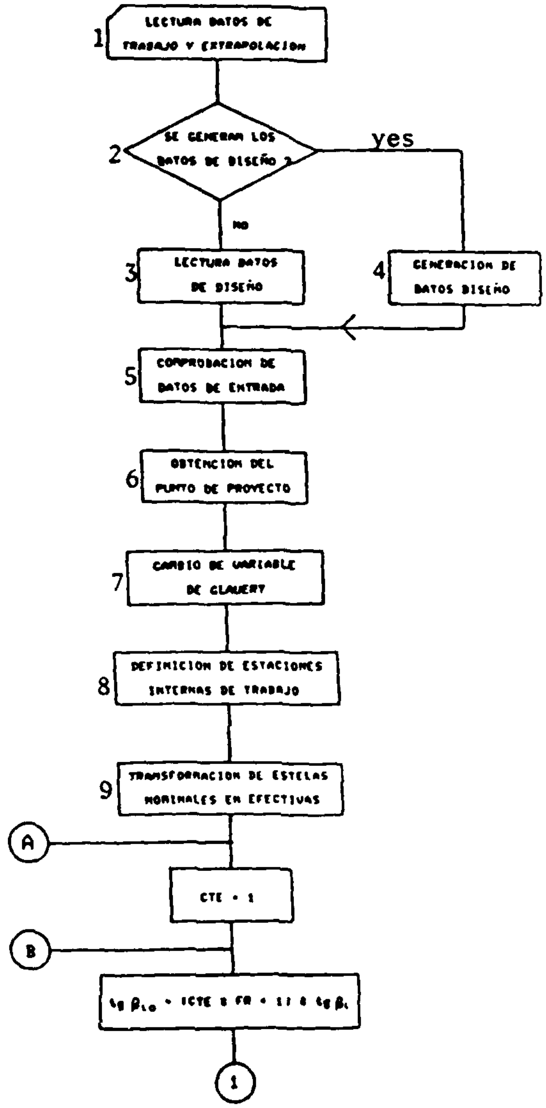

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Figure 1. The LDTH26 Program -- Simplified Flow Chart.
Key: 1, Reading of working and operating data; 2, Are the design data generated?; 3, Reading of design data; 4, Generation of design data; 5, Check of input data; 6, Acquisition of projection design (may be starting) ; 7, change of Glauert variable; 8, Definition of internal work stations; 9, Transformation of nominal wakes into actual ones.

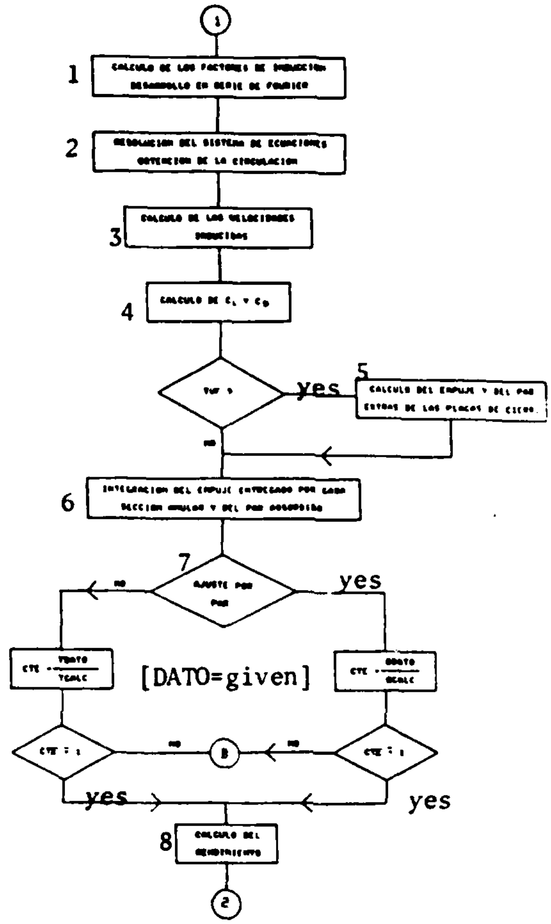

Figure 2.

Key: 1, Calculation of the induction factors - expansion into Fourier series; 2, Solution of system of equations - determination of circulation; 3, Calculation of induced velocities; 4, Calculation of C_L and C_D; 5, Calculation of thrust and turning moment - extras [sic] of the closures; 6, Integration of the thrust delivered by each annular section and the absorbed turning moment; 7, Adjustment in terms of turning moment; 8, Calculation of results.

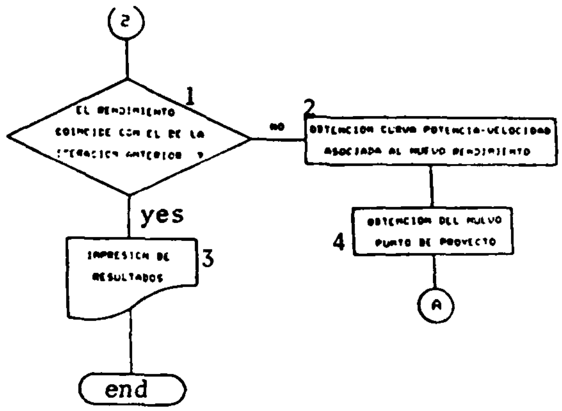

Figure 3.
Key: 1, Does result coincide with that of previous iteration?; 2, Plotting of power-velocity curve associated with new result; 3, Printing of results; 4, Acquisition of new starting point.

3.3. Comparison Between the Results Obtained With the Lifting Line Theory and With the New Propulsion Theory

3.3.1. Description of the example selected to make the comparison

The characteristics of the ship (a bulk carrier, of 30,000 DWT) which was selected to carry out these studies are as follows:

-- Length 178.00 m

-- Beam 28.80 m

-- Draft 10.65 m

-- Block coefficient 0.8353

-- Characteristics of the power plant:

MCR [expansion unknown] 10.900 BHP [expansion unknown]

Design rpm 123

After auto-propulsion tests were carried out with a stock propeller, the BB series developed by NSMB [expansion unknown] was used to calculate the optimum full-scale diameter for the ship in question, and it was found for 4 blades it would be 5.5 m.

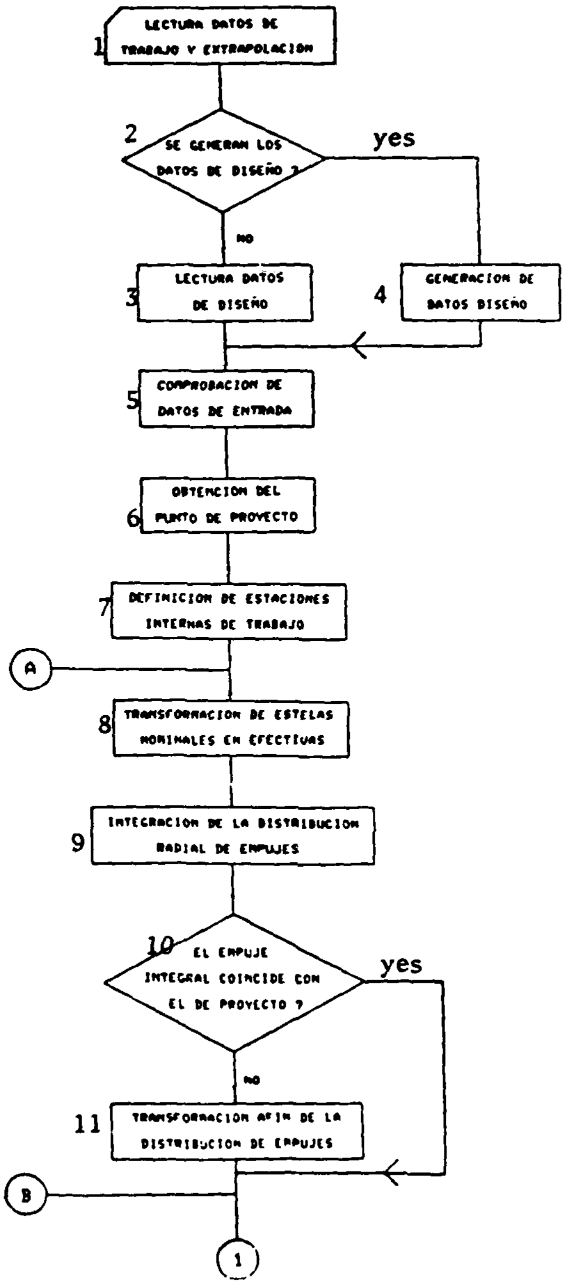

Figure 4. The LDTH28 Program -- Simplified Flow Chart.
Key: 1, Reading of working and operating data; 2, Are the design data generated?; 3, Reading of design data; 4, Generation of design data; 5, Check of input data; 6, Acquisition of design point 7, Definition of internal work stations; 8, Transformation of nominal wakes into actual wakes; 9, Integration of radial distribution of thrusts; 10, Does the integral thrust coincide with the projected thrust?; 11, Refined transformation of the thrust distribution.

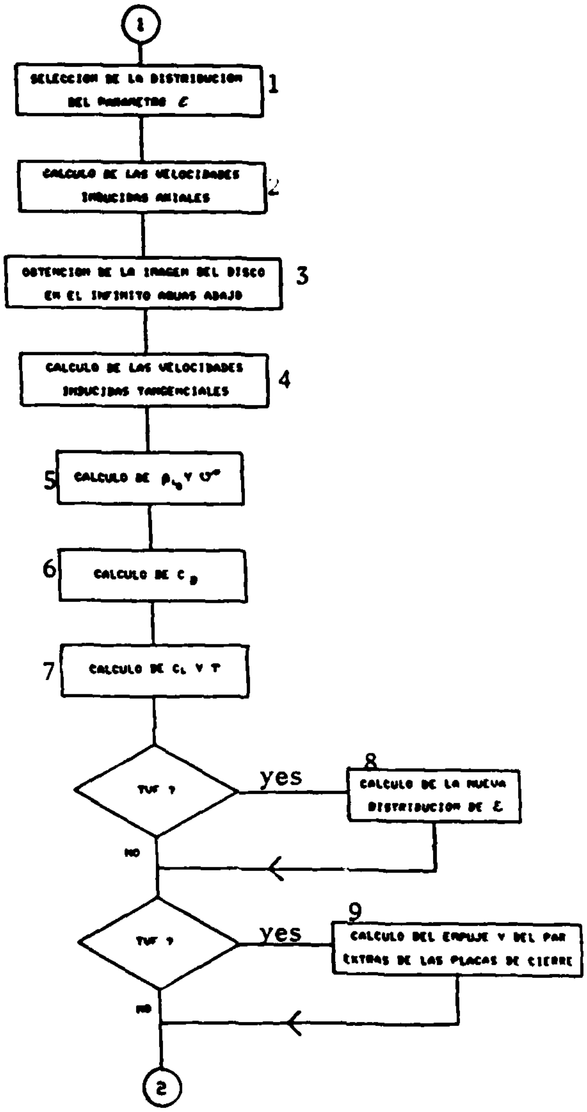

Figure 5.

Key: 1, Selection of the distribution of parameter ε; 2, Calculation of the induced axial velocities; 3, Acquisition of the image of the disc in infinity downstream; 4, Calculation of the induced tangential velocities; 5, Calculation of $\beta i_o + \nu^*$; 6, Calculation of C_D; 7, Calculation of C_L and T; 8, Calculation of the new distribution of ε; 9, Calculation of the thrust and turning moment -- extras [sic] of the closures.

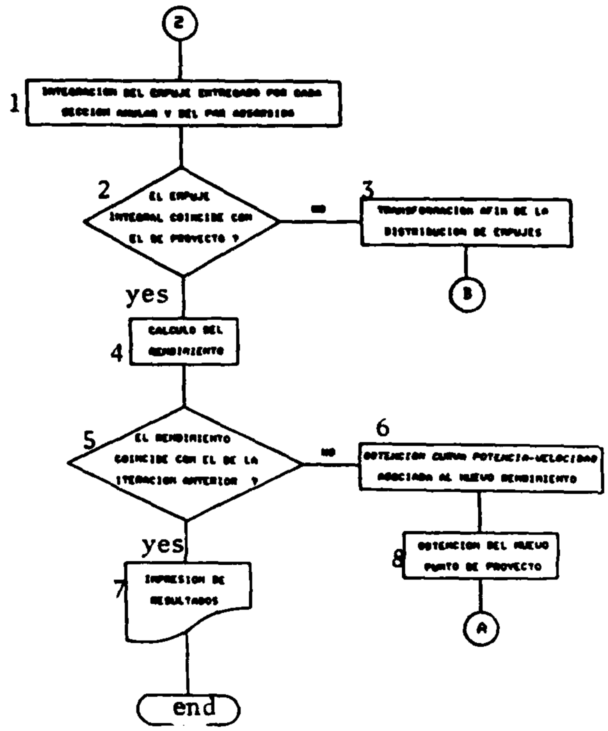

Figure 6.
Key: 1, Integration of the thrust delivered by each annular section and of the absorbed turning moment; 2, Does the integral thrust coincide with the design value?; 3, Refined transformation of the distribution of thrusts; 4, Calculation of output; 5, Does the result coincide with the previous iteration?; 6, Plotting of power-velocity curve associated with the new output; 7, Printing of results; 8, Acquisition of new design point.

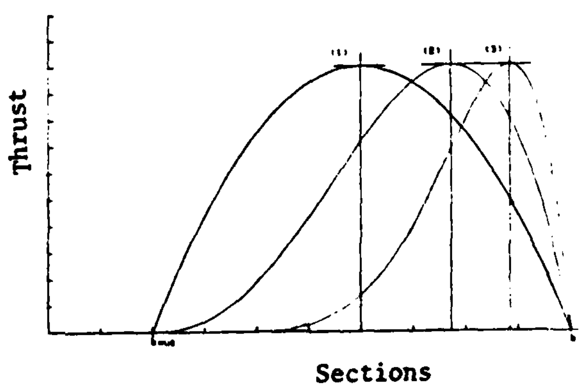

Figure 7.

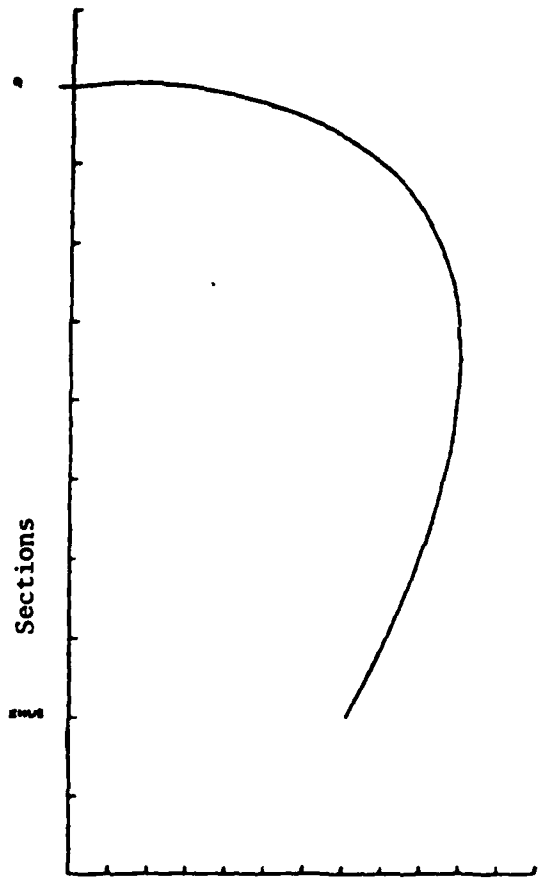

Figure 8.

Table 1 presents the results of the predictions of the full-scale behavior of the propeller which is to be designed by adapting it to a radial wake distribution. The expected product of the rotative--relative output times the output of the propeller in open water, according to series BB, is 0.5305. /274

Table 2 summarizes the radial distribution laws of the nominal wakes, chords and thicknesses which the propeller to be designed must have.

Sections

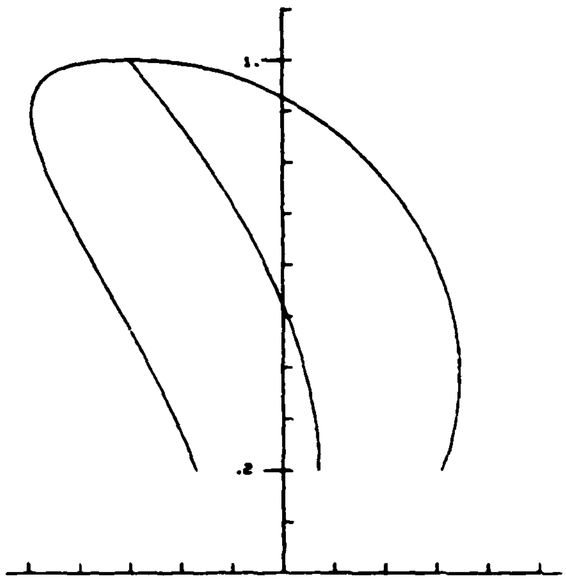

Figure 9. Distribution of Chords. Type: BB, 2:4, AE/AO:0.6.

3.3.2. Effect of the parameter ε on the results of the calculations which were carried out with the new propulsion theory

Figure 7 shows the appearance of the radial distribution laws of the thrust per unit of length which should be possessed by the propeller which is to be designed with the aid of the new propulsion theory.

When the theoretical principles of the new propulsion theory were presented, it was maintained that the output of the propeller is closely tied to the value of the parameter ε. In order to present /275 quantitative data on the sensitivity with which this parameter affects the output, a systematic series of design was made with the aid of this theory by varying the coefficient ε from 0.3 to 0.6.

Tables 3, 4, 5 and 6 summarize the results of the calculations mentioned above. Note that, despite the fact that these properties are defined at 50 stations, only the values corresponding to the most characteristic stations are presented.

Each of these tables includes the most characteristic hydrodynamic parameters of each of the designs.

In summary, it is obvious that as the parameter ε increases, the tangent of the hydrodynamic pitch angle and the magnitudes of the axial components of the induced velocities increase, but the magnitudes of the tangential components do not do so. We also clearly see the progressive decline in the output when the parameter ε increases.

TABLE 1. INITIAL PREDICTIONS OF THE BEHAVIOR OF THE PROPELLER

V	DHP	$1-W_{n}$	T
14	6.891	0,6490	59.570
15	9.258	0,6713	71.120
16	13.579	0,6873	92.220
17	19.424	0,6607	126.660

TABLE 2. RADIAL DISTRIBUTION OF CHORDS, THICKNESSES AND MEAN CIRCUMFERENTIAL VALUES OF THE NOMINAL WAKES

X_o	C_r	t	$1-W_n$
0,2	1,3200	0,2660	0,2340
0,3	1,5114	0,2370	0,2947
0,4	1,6690	0,2080	0,3533
0,5	1,7845	0,1790	0,4056
0,6	1,8505	0,1500	0,4513
0,7	1,8538	0,1200	0,4903
0,8	1,7589	0,0910	0,5290
0,9	1,4833	0,0660	0,5634
1,0	0,0000	0,0330	0,5950

TABLE 3. RESULTS OBTAINED BY MEANS OF THE PROPULSION THEORY WITH A CONSTANT VALUE OF ε = 0.3.

X	v^*	$\tan \beta_{io}$	C_L	Δv_i	$\Delta \omega_i$
0,2	7,7051	0,3791	—0,0143	0,0631	—0,1006
0,3	8,5978	0,8052	0,8967	2,0755	3,9312
0,4	12.1563	0,6018	0,6395	2,2899	3,7530
0,5	16.3128	0,4608	0,4298	2,2592	2,8952
0,6	20,2857	0,3798	0,3162	2,1204	2,2891
0,7	24.1753	0,3230	0,2416	1,9076	1,7898
0,8	28.0581	0,2787	0,1833	1,5736	1,3088
0,9	31,9541	0,2391	0,1306	1,0844	0,8010
1,0	36,0504	0,1892	0,0000	0,0006	—0,0010

$\eta_o = 0,5977$

TABLE 4. RESULTS OBTAINED BY MEANS OF THE PROPULSION THEORY WITH A CONSTANT VALUE OF ε = 0.4.

X	v^*	$\tan \beta_{io}$	C_L	Δv_i	$\Delta \omega_i$
0,2	7,4508	0,4375	0,0617	0,0968	0,1717
0,3	8,4086	0,9602	0,9785	2,5566	4,5527
0,4	12,5831	0,6344	0,5833	2,8285	3,5430
0,5	16,6325	0,4881	0,4024	2,8045	2,7638
0,6	20,5350	0,4011	0,2993	2,6462	2,1935
0,7	24,3668	0,3390	0,2301	2,3939	1,7183
0,8	28,1931	0,2898	0,1754	1,9889	1,2581
0,9	32,0290	0,2450	0,1253	1,3837	0,7706
1,0	36,0296	0,1860	0,0000	0,0014	—0,0009

$\eta_o = 0,5603$

TABLE 5. RESULTS OBTAINED BY MEANS OF THE PROPULSION THEORY WITH A CONSTANT VALUE OF ε = 0.5.

X	v*	tan $\beta_{i\infty}$	C_L	Δv_i	$\Delta\omega_i$
0,2	7,4859	0,3964	0,0216	0,1555	0,0734
0,3	8,6322	1,0358	0,9361	2,9998	4,6310
0,4	12,9345	0,6674	0,5461	3,3263	3,4099
0,5	16,9065	0,5146	0,3835	3,3113	2,6779
0,6	20,7522	0,4216	0,2876	3,1381	2,1305
0,7	24,5352	0,3547	0,2222	2,8521	1,6710
0,8	28,3126	0,3008	0,1699	2,3841	1,2244
0,9	32,0959	0,2512	0,1218	1,6730	0,7505
1,0	36,0117	0,1833	0,0000	0,0026	— 0,0009
		η_o = 0,5305			

TABLE 6. RESULTS OBTAINED BY MEANS OF THE PROPULSION THEORY WITH A CONSTANT VALUE OF ε = 0.6.

X	v*	tan $\beta_{i\infty}$	C_L	Δv_i	$\Delta\omega_i$
0,2	7,4888	0,4035	0,0213	0,1991	0,0748
0,3	8,9513	1,1105	0,9044	3,4413	4,6365
0,4	13,2135	0,7137	0,5351	3,8226	3,4136
0,5	17,1420	0,5484	0,3786	3,8175	2,6803
0,6	20,9469	0,4474	0,2852	3,6307	2,1323
0,7	24,6917	0,3746	0,2210	3,3125	1,6724
0,8	28,4293	0,3155	0,1694	2,7833	1,2254
0,9	32,1684	0,2607	0,1216	1,9676	0,7510
1,0	36,0117	0,1833	0,0000	0,0041	— 0,0009
		η_o = 0,5031			

3.3.3. Sensitivity of the lifting line theory to the type of radial distribution of circulation.

As we know, the output η_0 which is obtained with the lifting line theory is very sensitive to the type of radial distribution law of circulation.

In the past, especially for theoretical studies the Betz radial distribution law of load was widely used. This law is characterized by the fact that the ratio tan βi_0/tan βi is maintained constant radially.

Later, Van Manen and Lerbs proposed different radial distribution laws for the above-mentioned parameter (see, for example, the contents of Section 7.6.8 of [12]).

After the technical group which now makes up the Ship Engineering Department of SATENA made many propeller designs using the LDTH26 program, which was also designed and written by this group, it was possible to confirm that the Betz distribution law is physically inaccessible. This means that if propellers are designed utilizing this radial distribution law of load, the outputs which are obtained do not agree with any of those expected theoretically. On the other hand, the distributions of Van Manen and Lerbs are accessible, and it is also true that the Lerbs distribution law provides better results than that of Van Manen.

Tables 7, 8 and 9 present the results of the calculations performed with the aid of the lifting line theory when the radial distribution laws of load of Van Manen, Lerbs and Betz were used as input data. /276

TABLE 7. RESULTS OBTAINED FROM THE LIFTING LINE THEORY WITH A RTAN DISTRIBUTION OF THE VAN MANEN TYPE

X	v^*	$\tan\beta_{iw}$	C_L	Δv_i	$\Delta\omega_i$
0,2	6,7662	1,5760	0,0000	3,1740	3,4639
0,3	10,4515	1,0039	0,8090	4,2088	3,2563
0,4	14,2531	0,7096	0,6217	4,4201	2,5518
0,5	18,0121	0,5315	0,4353	0,0557	1,8101
0,6	21,6910	0,4145	0,2959	3,4132	1,2194
0,7	25,3086	0,3330	0,1962	2,6762	0,7850
0,8	28,9006	0,2715	0,1235	1,8318	0,4480
0,9	32,4640	0,2248	0,0683	1,0017	0,2063
1,0	36,0115	0,1885	0,0000	0,2063	0,0332

$\eta_o = 0{,}5236$

TABLE 8. RESULTS OBTAINED FROM THE LIFTING LINE THEORY WITH A RTAN DISTRIBUTION OF THE LERBS TYPE

X	v^*	$\tan\beta_i$	C_L	Δv_i	$\Delta\omega_i$
0.2	6.6499	1.1883	0.0000	2.4867	2.7911
0.3	10.4444	0.8120	0.6680	3.3037	2.5054
0.4	14.2442	0.6119	0.5191	3.5039	2.0078
0.5	17.9812	0.4854	0.3794	3.3402	1.5251
0.6	21.6517	0.3986	0.2763	3.0022	1.1335
0.7	25.2715	0.3356	0.2021	2.5928	0.8309
0.8	28.8732	0.2873	0.1469	2.1026	0.5833
0.9	32.4508	0.2495	0.1006	1.6055	0.3911
1.0	36.0151	0.2193	0.0000	1.1173	0.2407

$\eta_o = 0.5608$

It is obvious that the theoretical output expected from the Betz distribution law is higher than that expected from the other two load distribution laws.

These examples were presented as evidence of the imprecision of the lifting line theory when propellers are designed with significant radial load distributions at the ends of the blades. These distributions are mathematical rather than physical in nature since the associated large differences in pressure between the pressure and suction phases of the propeller cannot be achieved in reality.

TABLE 9. RESULTS OBTAINED FROM THE LIFTING LINE THEORY WITH A RTAN DISTRIBUTION OF THE BETZ TYPE

X	v*	$\tan\beta_{i}$	C_L	Δv_i	$\Delta\omega_i$
0.2	6.4700	0.5475	0.0000	0.4763	1.4100
0.3	10.3394	0.4596	0.3958	1.0053	1.2330
0.4	14.1442	0.4130	0.3251	1.4303	1.0977
0.5	17.8689	0.3796	0.2739	1.7822	1.0063
0.6	21.5345	0.3518	0.2398	2.0760	0.9410
0.7	25.1554	0.3278	0.2154	2.3240	0.8924
0.8	28.7610	0.3094	0.1959	2.5554	0.8629
0.9	32.3414	0.2930	0.1685	2.7596	0.8439
1.0	35.9073	0.2784	0.0000	2.9435	0.8316

$\eta_{io} = 0.5951$

Here we should emphasize that the new propulsion theory does not present these problems while at the same time it indicates the theoretical importance of the radial distribution law of load without at the same time giving it the output values which are obtained with the lifting line theory.

3.3.4. Comparison between similar designs carried out with the aid of the lifting line theory and the new propulsion theory

Figure 7 presents the three laws of radial distribution of the thrust per unit of length which were adopted as input data for carrying out designs with the aid of the new propulsion theory.

The results of the calculations performed with the aid of this theory are given in Tables 10, 11 and 12.

TABLE 10. RESULTS OBTAINED FROM THE PROPULSION THEORY WITH RADIAL THRUST DISTRIBUTION (1)

X	v*	$\tan\beta_{i}$	C_L	Δv_i	$\Delta\omega_i$
0.2	8.4486	0.2001	—0.2258	0.2235	—0.9931
0.3	10.8285	0.7268	0.7256	3.1518	1.8670
0.4	10.8989	0.9171	1.2237	3.5055	6.1254
0.5	16.0344	0.5523	0.5549	3.3277	3.6748
0.6	20.3862	0.4170	0.3349	2.9226	2.4370
0.7	24.4614	0.3332	0.2118	2.3831	1.5878
0.8	28.4017	0.2735	0.1303	1.7216	0.9416
0.9	32.2432	0.2254	0.0687	0.9433	0.4252
1.0	36.0114	0.1833	0.0000	0.0003	0.0001

$\eta_{io} = 0.5253$

In order for the design carried out with the aid of the lifting line theory to be more comparable to those given above, we opted to introduce, as input data for the calculations which were to be performed with the aid of this last theory, the radial distributions of /277 the parameters tan βi_o/tan βi which were obtained as the end result in the designs carried out with the aid of the new propulsion theory.

TABLE 11. RESULTS OBTAINED FROM THE PROPULSTION THEORY WITH RADIAL THRUST DISTRIBUTION (2)

X	v*	$\tan\beta_{io}$	C_L	Δv_i	$\Delta\omega_i$
0.2	7.5762	0.3754	— 0.0013	— 0.0089	— 0.0091
0.3	10.8696	0.3807	0.0739	0.6152	0.4681
0.4	13.9421	0.4271	0.2001	1.5774	1.3468
0.5	17.1016	0.4339	0.2863	2.3310	2.0223
0.6	20.4947	0.4099	0.3130	2.7932	2.2897
0.7	24.1272	0.3682	0.2912	2.9251	2.1536
0.8	27.9710	0.3183	0.2365	2.6451	1.6835
0.9	31.9596	0.2600	0.1545	1.8233	0.9479
1.0	36.0256	0.1855	0.0000	0.0048	— 0.0002

$\eta_{io} = 0.5534$

TABLE 12. RESULTS OBTAINED FROM THE PROPULSION THEORY WITH RADIAL THRUST DISTRIBUTION (3)

X	v*	$\tan\beta_{io}$	C_l	Δv_i	$\Delta\omega_i$
0.2	7.5302	0.3602	0.0000	0.0000	0.0000
0.3	11.1017	0.3027	0.0001	0.0013	0.0008
0.4	14.6673	0.2769	0.0047	0.0597	0.0330
0.5	18.1518	0.2741	0.0273	0.3731	0.2045
0.6	21.4673	0.2930	0.0850	1.1121	0.6515
0.7	24.5711	0.3221	0.1869	2.1848	1.4074
0.8	27.6391	0.3431	0.3119	3.1976	2.1936
0.9	31.2041	0.3205	0.3612	3.3765	2.1637
1.0	36.0196	0.1849	0.0000	0.0677	— 0.0039

$\eta_{o} = 0.5062$

Tables 13, 14 and 15 present, respectively, calculations which are mentioned above and are directly comparable to Tables 10, 11 and 12, respectively.

The most interesting conclusions which are derived from a comparison of the above-given tables are the following:

a) In both cases the value of the propeller's output in open water increases as the center of gravity of the radial distribution of load is shifted towards the end of the blade, and once a certain maximum value has been reached, decrease sets in.

TABLE 13. RESULTS OBTAINED BY MEANS OF THE LIFTING LINE THEORY WITH RADIAL THRUST DISTRIBUTION (1)

x	v^*	$\tan \beta_{io}$	C_L	Δv_t	$\Delta \omega_t$
0,2	8,4361	0,1979	0,0000	— 0,9208	— 1,1921
0,3	10,6727	0,7297	0,6896	3,0675	2,0003
0,4	14,3339	0,8240	0,6631	5,2587	3,1065
0,5	18,0464	0,5425	0,4536	4,1848	1,8521
0,6	21,7068	0,4103	0,2955	3,3287	1,1770
0,7	25,3163	0,3299	0,1930	2,5871	0,7558
0,8	28,9064	0,2723	0,1223	1,8262	0,4480
0,9	32,4725	0,2259	0,0676	1,0069	0,2053
1,0	36,0195	0,1851	0,0000	0,0608	0,0036

$\eta_{io} = 0,5292$

TABLE 14. RESULTS OBTAINED BY MEANS OF THE LIFTING LINE THEORY WITH RADIAL THRUST DISTRIBUTION (2)

x	v^*	$\tan \beta_{io}$	C_L	Δv_t	$\Delta \omega_t$
0,2	6,6683	0,3684	0,0000	— 0,2942	0,8270
0,3	10,5386	0,3840	0,3034	0,5021	0,7873
0,4	14,3284	0,4308	0,3183	1,7363	1,0057
0,5	18,0143	0,4376	0,3131	2,6993	1,1997
0,6	21,6528	0,4133	0,2855	3,2392	1,2342
0,7	25,2688	0,3714	0,2416	3,3293	1,0989
0,8	28,8910	0,3213	0,1874	2,9450	0,8256
0,9	32,5010	0,2633	0,1209	2,0033	0,4458
1,0	36,0729	0,1884	0,0000	0,0696	— 0,0279

$\eta_{io} = 0,5668$

TABLE 15. RESULTS OBTAINED BY MEANS OF THE LIFTING LINE THEORY WITH RADIAL THRUST DISTRIBUTION (3)

x	v^*	$\tan \beta_{io}$	C_L	Δv_t	$\Delta \omega_t$
0,2	6,7277	0,3622	0,0000	— 0,2729	0,7588
0,3	10,5161	0,3041	0,1829	— 0,1688	0,5655
0,4	14,2451	0,2786	0,1444	— 0,0460	0,4467
0,5	17,9365	0,2776	0,1451	0,3547	0,4281
0,6	21,6060	0,2999	0,1764	1,2658	0,5588
0,7	25,2180	0,3332	0,2180	2,6012	0,8708
0,8	28,7863	0,3571	0,2431	3,8870	1,2285
0,9	32,4283	0,3361	0,2121	4,1610	1,1418
1,0	36,2350	0,1861	0,0000	0,1086	— 0,2021

$\eta_{io} = 0,5395$

b) The outputs obtained in Tables 12 and 15 are dissimilar. This fact reveals how the propulsion theory does not make the mistakes which are characteristic of the lifting line theory.

c) The results obtained with the two theories agree until the maximum value of n_o is reached. Starting with this distribution, the results provided by the lifting line theory are unreal [may also be "imaginary" or "unrealistic"], while those provided for by the new propulsion theory are closer to reality.

d) The tangential components of the induced velocities which are obtained with the aid of the new propulsion theory are higher than the corresponding values obtained with the aid of the lifting line theory.

e) The axial components of the induced velocities [obtained] with the aid of the new propulsion theory are lower than the corresponding values of the lifting line theory.

It must be mentioned that the values of ε which were used in the designs which are being compared in this section were sufficient to determine that the axial components of the velocities induced in the propeller disc were half of the similar components corresponding to infinity downstream from the propeller.

e) The hydrodynamic pitch angles corresponding to the 0.7 stations which are obtained with both theories are found to be reasonably equal and the same is true of C_L coefficients corresponding to these stations.

It should be pointed out that the induced axial velocities which appear in some of the calculations carried out with the aid of the new propulsion theory are due to the fact that the radial thrust distribution which is used is not adequate from the physical standpoint and within the framework of this theory.

In order to supplement the analyses, the new propulsion theory was used to repeat the design, the characteristics of which are given in Table 9 (the radial distribution of the parameter tan βi_o/tan βi proposed by Betz).

In order to be able to make this comparison, it was necessary to expand the capabilities of the LDTH28 program in such a way that it could accept the circulation distribution law as an input datum. This was possible because this law is directly dependent on the law of the radial distribution of thrust per unit of length (see equations (12), (14), (15) and (20)).

The results of the calculations are given in Table 16. Note that the result obtained in this case is 0.5730, which is significantly lower than that provided by the lifting line theory (0.5951) and is consistent with the best full-scale results obtained. /278

TABLE 16. RESULTS OBTAINED WITH THE PROPULSION THEORY WITH A RADIAL CIRCULATION DISTRIBUTION OF THE BETZ TYPE

X	v^*	$\tan \beta_\infty$	C_L	Δv_t	[illegible]
0,2	7,6010	0,4019	— 0,0022	0,1798	0,0464
0,3	9,6642	0,6430	0,4435	1,9434	2,4979
0,4	13,3753	0,5176	0,3547	2,2132	2,2902
0,5	17,0775	0,4404	0,2951	2,3640	2,0814
0,6	20,7520	0,3865	0,2560	2,4537	1,8964
0,7	24,4163	0,3441	0,2281	2,4810	1,7069
0,8	28,1120	0,3083	0,2059	2,3890	1,4728
0,9	31,8700	0,2712	0,1832	2,0662	1,1206
1,0	36,0395	0,1879	0,0000	0,0303	— 0,0014

$\eta_o = 0,5730$

4. Conclusions

The contents of the present work indicate that a new propulsion theory has been developed which is correct from the theoretical standpoint and which offers the important advantage, compared to the theories which are currently in use, of being more precise and of predicting what occurs in infinity downstream from the propeller with allowance for the contraction of the liquid stream.

By virtue of its generality, this theory is applicable to the case of extremely heavily loaded propellers and in those where the radial contraction of the liquid stream exerts or possesses a significant effect.

It should be emphasized that, in addition to the above-mentioned advantages, the new theory is extraordinarily simple to use and also that the calculations which are performed require a considerably smaller amount of computer time than that of the lifting line theory.

The authors noted that the students of Engines of the Superior Technical School of Naval Engineers, who received scholarships from SATENA carried out the calculation process described above using small computers within a period of less than four hours.

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List of Symbols

A = Area of drive disc

C_r = Mean chord of the annular section of a generic blade

I = Moment of inertia of the mass of water which traverses the drive disc per unit of time.

$I_{-\infty}$ = Moment of inertia of the water which flows with the stream of liquid in infinity downstream from the propeller

M = Turning moment absorbed by the drive disc

M_1 = Turning moment exerted by the drive disc on the fluid

R = Radius of the propeller

T = Thrust provided by the propeller

dD = Viscous resistance corresponding to an annular element of the propeller

dL = Lift corresponding to an annular element of the propeller

dM = Turning moment absorbed by an annular element of the propeller

dT = Thrust provided by an annular element of the propeller

c_D = Coefficient of viscous resistance of the annular section of a generic blade

c_L = Lift coefficient of the annular section of a generic blade

r = Mean radius corresponding to an annular element of the propeller

r_h = Radius of the core of the propeller

d_r = Width of the annular section of a generic blade

P_o = Equilibrium pressure of the fluid

Δp = Pressure variation produced in the fluid by the drive disc

v = Velocity with which the drive disc advances within the fluid

v^* = Modulus of the velocity with which the fluid strikes the annular section of a generic blade

v_B = Velocity of the ship at design power

Δv_1 = Velocity induced by the propeller in the fluid on the section corresponding to the disc

Δv_2 = Velocity induced by the propeller in the fluid in infinity downstream

w_{tr} = effective wake, identical to the thrust corresponding to the mean radius of the annular section of a generic blade

z = Number of propeller blades

βi = Angle of incidence, with respect to the blade, of the vector, relative velocity of the fluid with respect to the propeller disregarding the induced velocities

βi_o = Hydrodynamic pitch angle corresponding to the annular section of a generic blade

ϵ = Coefficient of the distribution of pressure on the faces of the drive disc

ρ = Density of the fluid

ω = Angular velocity of rotation of the propeller

$\Delta\omega_1$ = Angular velocity of the fluid as it passes through the drive disc

$\Delta\omega_2$ = Angular velocity induced by the propeller in the fluid in infinity downstream.

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